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Abstract

This study examines the properties of fiber-reinforced reactive powder concrete (FR-RPC). Steel fibers, glass fibers, and steel-glass hybrid fibers were used to prepare the FR-RPC. The non-fibrous reactive powder concrete (NF-RPC) was prepared as a reference mix. The proportion of fibers by volume for all FR-RPC mixes was 1.5%. Steel fibers of 13 mm length and 0.2 mm diameter were used to prepare the steel fiber-reinforced RPC (SFR-RPC). Glass fibers of 13 mm length and 1.3 mm diameter were used to prepare the glass fiber-reinforced RPC (GFR-RPC). The hybrid fiber-reinforced RPC (HFR-RPC) was prepared by mixing 0.9% steel fibers and 0.6% glass fibers. Compressive strength, axial load-axial deformation behavior, modulus of elasticity, indirect tensile strength, and shear strength of the RPC mixes were investigated. The results showed that SFR-RPC achieved higher compressive strength, indirect tensile strength and shear strength than NF-RPC, GFR-RPC, and HFR-RPC. Although the compressive strengths of GFR-RPC and HFR-RPC were slightly lower than the compressive strength of NF-RPC, the shear strengths of GFR-RPC and HFR-RPC were higher than that of NF-RPC.

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Mechanical Properties of Steel, Glass and Hybrid Fibre Reinforced Reactive Powder Concrete

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Abstract

This study examines the properties of fibre-reinforced reactive powder concrete (FR-RPC). Steel fibres, glass fibres and steel-glass hybrid fibres were used to prepare the FR-RPC. The non-fibrous RPC (NF-RPC) was prepared as a reference mix. The proportion of fibres by volume for all FR-RPC mixes was 1.5%. Steel fibres of 13 mm length and 0.2 mm diameter were used to prepare the steel fibre-reinforced RPC (SFR-RPC). Glass fibres of 13 mm length and 1.3 mm diameter were used to prepare the glass fibre-reinforced RPC (GFR-RPC). The hybrid fibre-reinforced RPC (HFR-RPC) was prepared by mixing 0.9% steel fibres and 0.6% glass fibres. Compressive strength, axial load-axial deformation behaviour, modulus of elasticity, indirect tensile strength, and shear strength of the RPC mixes were investigated. The results showed that SFR-RPC achieved higher compressive strength, indirect tensile strength and shear strength than NF-RPC, GFR-RPC and HFR-RPC. Although the compressive strengths of GFR-RPC and HFR-RPC were slightly lower than the compressive strength of NF-RPC, the shear strengths of GFR-RPC and HFR-RPC were higher than that of NF-RPC.

KEYWORDS: Reactive powder concrete, steel fibre, glass fibre, hybrid fibre.

1. Introduction

Reactive powder concrete (RPC) is a special type of high performance concrete (HPC), which was introduced by Richard and Cheyrezy [1] in France in 1995. The dense structure of RPC is formed mainly by cement, silica fume, fine aggregate, water, and superplasticiser with the absence of the coarse aggregate. The RPC possesses superior mechanical and durability properties compared to other types of HPC. Nevertheless, like high strength concrete, RPC is susceptible to brittle failure. One of the methods to increase the ductility of the RPC is the addition of fibres. Steel fibres have long been used for this purpose [2-5].

Richard and Cheyrezy [1] prepared RPC with a compressive strength of 200 MPa. Over the last two decades, however, many researchers prepared the RPC by using the available materials with different mix components and curing methods. The prepared RPC cured by using standard curing conditions (water tank with a temperature range of 20-25 ^{o}C) achieved compressive strength ranging between 84 MPa to 212 MPa [4, 6-9]. Liu and Huang [10] prepared highly flowable RPC cured under autoclave technique, which achieved only 75 MPa. The low compressive strength of the RPC prepared by Liu and Huang [10] can be attributed to the high flowability of the RPC. Ahmed et al. [11] also found that increasing the flowability of the RPC by increasing the dosage of superplasticiser and decreasing the grading of the sand decreased the compressive strength of the RPC [11].

Richard and Cheyrezy [1] recommended using steel fibres of 2% by volume in the RPC. The influence of the volume fraction of the steel fibres on the compressive strength of the RPC varies depending on the type of the steel fibres. Al-Tikrite and Hadi [9] revealed that the compressive strength of RPC increased by increasing proportion of micro steel fibres from 1% to 4% by volume. However, Al-Tikrite and Hadi [9] also found that increasing proportion of deformed steel fibres from 1% to 4% by volume had a marginal effect on the compressive strength of the RPC [9]. Yunsheng et al. [3] prepared RPC using 0%, 2%, 3%, and 4% of steel fibres (13 mm long with diameter 0.175 mm) by volume. The results demonstrated that the RPC with 4% of steel fibres by volume achieved higher compressive strength than RPC with 0%, 2% and 3% steel fibres by volume. Ju et al. [12] reported that the RPC mix with 1.5% steel fibres (13 mm long with diameter 0.2 mm) by volume achieved higher compressive strength and tensile strength than the RPC mix with 0% and 1% steel fibres (13 mm long with diameter 0.2 mm) by volume.

Recently, Al-Tikrite and Hadi [9] investigated the influence of micro steel fibres, industrial deformed steel fibres and waste steel fibres on the mechanical properties of RPC. The results showed that micro steel fibre reinforced RPC achieved higher strength than the RPC with industrial and waste steel fibres. Also, the RPC with waste steel fibres achieved higher strength and ductility than non-fibrous reactive powder concrete (NF-RPC) and achieved comparable strength and ductility to the RPC with industrial steel fibres.

It was found from an extensive literature review that only a few studies investigated the effect of replacing the steel fibres by the other types of fibres in the RPC, especially to enhance the durability of the RPC in aggressive environments. For instance, Shaheen and Shrive [13] used carbon fibres (3 mm long with a fibre to cement ratio of 0.125 by weight) to produce more durable RPC against freezing and thawing than steel fibre reinforced RPC (SFR-RPC). It was found that carbon fibre reinforced RPC and SFR-RPC (12 mm long steel fibres with a fibre to cement ratio of 0.2 by weight) achieved comparable durability against freezing and thawing. Also, carbon fibre reinforced RPC achieved significantly higher compressive strength, tensile strength and fracture toughness than NF-RPC. Sanchayan and Foster [14] used 2% by volume of hybrid steel-polyvinyl alcohol (PVA) fibres to alleviate the explosive behaviour of the RPC at high temperature. The test results revealed that RPC with 1% PVA by volume plus 1% steel fibres by volume (50% steel fibres) achieved higher compressive strength than the RPC with hybrid fibres containing 25% or 75% steel fibres by volume plus the remaining percentage of PVA fibres (total 2% by volume of hybrid fibres). Also, Canbaz [15] reported that RPC with 1% by volume of polypropylene fibres achieved higher compressive strength than the RPC containing 0.5% and 1.5% polypropylene fibres by volume before and after the exposure to high temperature.

Cement mortar with glass fibre (called glass fibre reinforced concrete, GFRC) has been used in many architectural applications. In addition, the premix of GFRC has been used in some structural members with compressive strengths ranging between 40 MPa and 60 MPa [16]. The GFRC has also been used in other civil engineering applications, which include construction of permanent formwork, lining of sewer trunk line, bulky headwall, storage structures, and roofs [17]. Considering the excellent corrosion resistance and the low self-weight of glass fibres, the inclusion of glass fibres and steel-glass hybrid fibres in the RPC needs to be investigated.

This study investigates the compressive strength, axial load-axial deformation behaviour, modulus of elasticity, indirect tensile strength and shear strength of RPC containing 1.5% by volume of three different types of fibres: steel, glass, and hybrid steel-glass fibres.

2. Experimental program

2.1 Materials

General purpose (Type GP) cement according to AS 3972-2010 [18] was used for all mixes of non-fibrous reactive powder concrete (NF-RPC) and fibre-reinforced reactive powder concrete (FR-RPC). Densified silica fume was used as a supplementary cementitious material. This form of amorphous silica is a condensed silica fume manufactured by the SIMCOA silicon plant in Western Australia [19] and was supplied by the Australasian (iron & steel) Slag Association [20]. Washed fine river sand with particles size between 0.15 mm and 0.6 mm and fineness modulus of 1 was used to prepare all the RPC mixes. The superplasticiser used in this study was Sika viscocrete PC HRF-2 [21]. Tap water was used in all the RPC mixes. Steel fibres, glass fibres and hybrid steel-glass fibres were used in this study. The steel fibres were 13 mm long and had 0.2 mm diameter with a nominal tensile strength of 2500 MPa. Steel fibres were supplied by Steel Wire Fibre in China [22]. The glass fibres were high integrity alkali resistant glass (ARG) fibres, which were 13 mm long and had 1.3 mm diameter with a nominal tensile strength of 1500 MPa [23]. Glass fibres were produced by NEG, Japan [23]. In this study, FR-RPC was prepared by adding

1.5% fibres by volume. The hybrid fibres were a mix of 0.9% steel fibres and 0.6% glass fibres by volume. Steel and glass fibres used in this study are shown in Fig. 1. The properties of the steel and glass fibres are listed in Table 1.

2.2 Mix proportioning and casting

Four RPC mixes were prepared based on the mix proportion suggested in Richard and Cheyrezy [1]. However, some modifications were carried out due to the use of local materials and the addition of fibres. The mix design of NF-RPC consisted of 880 kg/m^3 cement, 220 kg/m^3 silica fume, 924 kg/m^3 fine sand, 48.4 l/m^3 superplasticiser and 158.4 kg/m^3 water. The steel fibre reinforced reactive powder concrete (SFR-RPC), glass fibre reinforced reactive powder concrete (GFR-RPC), and hybrid-fibre reinforced reactive powder concrete (HFR-RPC) were prepared by adding 1.5% steel fibres, 1.5% glass fibres and 1.5% hybrid fibres (0.9% of steel fibre plus 0.6% of glass fibre) by volume, respectively. The combination of 0.9% steel fibre and 0.6% glass fibre was used, based on a preliminary study by the authors. The proportion of fibres (1.5%) was selected based on the experimental study in Ju et al. [12]. A small amount of the superplasticiser and water were added to SFR-RPC, GFR-RPC and HFR-RPC mixes in order to keep the workability close to the workability of the reference mix (NF-RPC). The water content and superplasticiser dosage for the FR-RPC mixes was 163.7 kg/m3 and 52.8 l/m3, respectively.

The RPC batches were mixed using a vertical pan mixer at 15 revolutions per minute. The pan mixer was charged with the dry materials. The mixer was operated for about 5 minutes to maintain uniformity of the dry materials. Afterwards, water mixed with superplasticiser was added gradually. First, about two-thirds of the fluid (water mixed with superplasticiser) was added and mixed for about four minutes then the rest of the fluid was added. The average total mixing time for the NF-RPC mix was about 18 minutes. The addition of the fibres was the last step in the mixing process. The fibres were added to the mix by using a 16 mm sieve fixed on the mixer mesh cover during the mixing operation. No balling was observed during the addition and mixing of both steel and glass fibres. In total, the average mixing time was about 23 minutes for the FR-RPC. Workability of NF-RPC and FR-RPC mixes was examined by applying flow table test according to ASTM C230/C230M-14 [24] (Fig. 2). The ASTM C230/C230M-14 [24] was also used to test the workability in Al-Tikrite and Hadi [9] and Malik and Foster [25]. The test was conducted before casting the specimens. Only 15 drops were performed and the average flow diameter of the RPC mixes was measured. The 15 drops achieved a reasonable average flow diameter (200 mm) for the NF-RPC. Therefore, the 15 drops were taken as a reference. The average flow diameters for the SFR-RPC, GFR-RPC and HFR-RPC were 190 mm, 180 mm and 185 mm, respectively, as presented in Table 2.

The RPC specimens were cast and compacted in layers inside the moulds according to the recommendations of the standards [26-29]. The test specimens were compacted using a table vibrator. Next, the specimens were covered with plastic sheets until the demoulding of the specimens on the following day. Finally, the specimens were cured in a water tank with a temperature range of 20-25 °C.

2.3 Test matrix

Three specimens each were tested to determine the properties investigated in this study. Two different standard cylinder specimens were used: 100 mm × 200 mm cylinder specimens for the compressive strength test and 150 mm × 300 mm cylinder specimens for the modulus of elasticity and the splitting tensile strength tests. Also, 100 mm × 100 mm × 500 mm prism specimens were used for the shear strength test. All tests were carried out at 28 days except the compressive strength test of the NF-RPC which was carried out at 7, 28 and 56 days to determine the gain in the compressive strength.

2.4 Test method of compressive strength

The compressive strength of all the specimens was determined according to AS 1012.9-2014 [26]. A standard compression machine with a capacity of 1800 kN was used for the compressive strength test.

2.5 Test method of axial load-axial deformation behaviour and modulus of elasticity

The axial load-axial deformation behaviour and modulus of elasticity of the RPC mixes were investigated. The test was conducted according to AS 1012.17-2014 [27] by using a Denison compression machine with a capacity of 5000 kN. The test was performed with 150 mm × 300 mm cylinder specimens. The specimens were capped with high strength plaster and tested after two hours of removing from the curing tank. A standard compressometer with a linear variable differential transducer (LVDT) was used to measure the axial deformation. The compressometer was positioned symmetrically at the mid-height of the specimen, as shown in Fig. 3. The length over which the axial deformation was measured was 114 mm. The axial load was obtained directly from the test machine. The test was performed under a displacement-control loading of 0.3 mm per minute. The data were acquired through a Data Acquisition System. The modulus of elasticity was determined using Eq. (1):

$$E = \frac{G_2 - G_1}{\varepsilon_2 - 0.00005} \tag{1}$$

where E = modulus of elasticity (MPa), G_2 = stress that equals to 40% of the average compressive strength (MPa), G_1 = stress at 0.00005 axial strain (MPa) and ε_2 = axial strain at G_2 (mm/mm).

2.6 Test method of indirect tensile strength

Indirect tensile strength of the RPC was determined by the Brazilian test according to AS 1012.10-2014 [28]. Cylinder specimens of 150 mm × 300 mm were used to perform the test. A compression machine with a capacity of 1800 kN was used to perform the indirect tensile strength test (Fig. 4). Splitting tensile strength was determined by using Eq. (2).

$$T = \frac{2000P}{\pi DL} \tag{2}$$

where T = splitting tensile strength (MPa), P = maximum applied load (kN), D = diameter of specimen (mm), L = length of specimen (mm) and π = 3.14.

2.7 Test method of direct shear strength

Shear strength test for NF-RPC and FR-RPC was conducted according to JSCE SF6-1999 [29] Prism specimens with dimensions of 100 mm × 100 mm × 500 mm were used to perform the test. The test was conducted with some modifications to create stress concentration. Two notches were created around the entire test specimen (Figure 5). The notches were created on the hardened specimens by using an electric saw. Each notch had a depth of 10 mm and a width of 2.5 mm. The load was applied by using two steel loading edges. The out-to-out distance between the steel loading edges was the same of the clear distance between the notches (100 mm). The specimen was supported by two rigid steel blocks. The clear distance between the rigid steel blocks was 105 mm. The schematic diagram of the test setup is shown in Fig. 5. A standard hydraulic machine with a capacity of 300 kN was used for the test. The test setup of the direct shear test is shown in Fig. 6.

3. Results and discussion

3.1 Compressive strength of NF-RPC and FR-RPC

Figure 7 shows age versus compressive strength for NF-RPC. The average compressive strength of NF-RPC at 28 days was 90 MPa and the ratio of the 7-day compressive strength to the 28-day compressive strength was 88%. It is noted that the ratio of the compressive strength at 7 days to the compressive strength at 28 days of NF-RPC is higher than that of normal strength concrete, which is usually about 66% [30]. Hence, the ratio of the compressive strength at 7 days to the compressive strength at 28 days for the RPC is higher than that of the normal strength concrete by about 33%. This indicates that RPC can be a suitable option for concrete structural members that need high early compressive strengths such as columns on the ground floor of high-rise buildings and footbridges. However, the ratio of the 56-day compressive strength to the 28-day compressive strength of NF-RPC was about 113%, which is the same as the ratio of the 56-day compressive strength to the 28-day compressive strength for the normal strength concrete [30].

As reported in above, the average compressive strength of NF-RPC was 90 MPa at 28 days which can be considered relatively low for the RPC. The low compressive strength of NF-RPC can be attributed to the high dosage of the superplasticiser that increased the air content in the RPC matrix and led to inadequate compaction. The other possible reason for the relatively low compressive strength of NF-RPC was the relatively high flowability of the NF-RPC (the average flow diameter of NF-RPC was 200 mm). The average compressive strength of SFR-RPC was 96 MPa. The increase in the compressive strength of SFR-RPC compared to the compressive strength of NF-RPC was due to the addition of steel fibres. The presence of the discrete steel fibres in the SFR-RPC matrix decreased the lateral tensile stresses and increased energy absorption capacity of SFR-RPC and led to an increase in the compressive strength [5]. Similar findings were also reported in Ju et al. [12]. Ju et al. [12] reported that SFR-RPC containing 1.5% steel fibres by volume achieved higher compressive strength than NF-RPC. In contrast, the average compressive strengths of GFR-RPC and HFR-RPC were 81 MPa and 85 MPa, respectively, as presented in Table 2. The lower compressive strength for GFR-RPC compared to that of NF-RPC was probably due to the high aspect ratio of the glass fibres (aspect ratio = 10), which formed extra air voids and caused the premature failure. However, the reduction in the compressive strength for GFR-RPC was only 10%, which is less than the reduction of the compressive strength (25% reduction) reported for the addition of polypropylene fibres in RPC in Canbaz [15]. The compressive strength of the HFR-RPC was only 5.5% lower than that of NF-RPC. The lower reduction in the compressive strength of the HFR-RPC compared to that of GFR-RPC was due to the presence of the steel fibre in the HFR-RPC. The steel fibre in HFR-RPC was 60% of the total volume of the fibres. This percentage of steel fibres decreased the reduction in the compressive strength of the HFR-RPC.

Typical failure modes for the NF-RPC and FR-RPC investigated in this study under axial compressive load are shown in Fig. 8. The failure of the NF-RPC was explosive with a loud sound. The failure of the SFR-RPC, HFR-RPC and HFR-RPC was ductile with vertical cracks along the specimens.

3.1 Axial load-axial deformation behaviour of NF-RPC and FR-RPC

Figure 9 shows typical axial load-axial deformation behaviour for the NF-RPC and FR-RPC. The axial load-axial deformation behaviour of NF-RPC under uniaxial compression was linear up to failure and all the specimens failed suddenly in an explosive manner at the peak axial load. The addition of steel fibres, glass fibres and hybrid fibres prevented the sudden failure. The SFR-RPC showed the most ductile behaviour compared to the GFR-RPC and HFR-RPC. The axial load-axial deformation behaviour of SFR-RPC exhibited significant deformation after the maximum axial load. Afterwards, the axial load of the SFR-RPC dropped and decreased steadily with increasing deformation (softening response). The softening response dominated the axial load-axial deformation behaviour of SFR-RPC up to the end of the test. The steel fibres contributed in the ductile response of the SFR-RPC by extending the post-peak branch of the axial load-axial deformation behaviour. It is well known that steel fibres arrest the propagation of cracks and delay the onset of cracks in the concrete [31, 32]. The GFR-RPC and HFR-RPC specimens failed with a significant drop in the axial load after the maximum axial load. However, the drop in the axial load of the HFR-RPC followed by a decrease in the axial load with increasing axial deformation up to the end of the test.

Figure 10 shows typical stress-strain behaviour for the NF-RPC and FR-RPC. The NF-RPC had an average modulus of elasticity of 39 GPa. The average modulus of elasticity of SFR-RPC was 40 GPa and the average modulus of elasticity of HFR-RPC was 39 GPa. It is noted that steel and hybrid (steel+glass) fibres used in this study had a marginal effect on the modulus of elasticity. The average modulus of elasticity of GFR-RPC was 37 GPa. The lower modulus of elasticity for

GFR-RPC compared to that of NF-RPC was attributed to the lower compressive strength of GFR-RPC.

3.3 Indirect tensile strength of NF-RPC and FR-RPC

The average indirect tensile strength increased by the addition of steel and hybrid fibres from 7.6 MPa for NF-RPC to 9.9 MPa for SFR-RPC and 9.1 MPa for HFR-RPC (Table 2). The average indirect tensile strength of GFR-RPC decreased compared to that of NF-RPC. The average indirect tensile strength of GFR-RPC was found to be 5.7 MPa (Table 2). The lower indirect tensile strength for GFR-RPC compared to that of NF-RPC could be explained by the failure type of fibre reinforced concrete composite. Failure of fibre reinforced concrete composite occurred by either the slippage or breaking of fibres based on the generated bond between the matrix material and fibres [33]. In this study, the tensile failure can be associated with the slippage of fibres due to the weak bond of the glass fibres with RPC matrix. This was probably due to the insufficient chemical treatment of fibre surface, which was required to make the surface texture structurally suitable to resist the high tensile stresses within the RPC matrix. Typical failure modes for the SFR-RPC, GFR-RPC and HFR-RPC under splitting tensile test are shown in Fig. 11.

3.4 Direct shear strength of NF-RPC and FR-RPC

The direct shear test was conducted with some modifications of the recommendations in JSCE SF6-1999 [29]. Two notches around the test specimens were formed to induce double shear failure. However, all the RPC test specimens failed under direct shear load in one side only. This is probably because the specimens were not restrained at the supports. Hence, the shear strength was calculated according to Eq. (3), considering single shear failure.

$$\tau = \frac{1000P}{BH} \tag{3}$$

where, τ = shear strength (MPa), P = maximum applied load (kN), B = effective width of specimen (mm) and H = effective height of specimen (mm).

Some of the shear failure modes are shown in Fig. 12. The test observations revealed that the single shear failure of NF-RPC was typical and sudden at the maximum load and identical to the failure of SFR-RPC, HFR-RPC and GFR-RPC.

A significant improvement in the direct shear strength of NF-RPC occurred by the addition of the fibres. The average direct shear strength increased clearly from 10 MPa for NF-RPC to 25 MPa for SFR-RPC, 16 MPa for GFR-RPC and 22 MPa for HFR-RPC (Table 2). Maroliya [34] also found that the shear strength of RPC increased with the addition of steel fibres. Boulekbache et al. [35] reported that the addition of steel fibres increased the direct shear strength of both normal and high strength concrete. Although RPC had no coarse aggregate, the direct shear strength of the RPC increased with the addition of steel fibres.

Based on the results of this study, it was observed that SFR-RPC exhibited superior performance compared to NF-RPC, GFR-RPC and HFR-RPC. In particular, SFR-RPC attained higher compressive strength, modulus of elasticity, splitting tensile strength as well as shear strength than NF-RPC, GFR-RPC and HFR-RPC. However, this study demonstrated that FR-RPC could be produced by the addition of glass or steel-glass hybrid fibres. The GFR-RPC and HFR-RPC can be considered as alternatives of SFR-RPC when the use of only steel fibres in the RPC mix is not desirable (e.g., structural RPC members exposed to corrosive environment). This study also showed that the addition of fibres (steel, glass and steel-glass) in the RPC matrix could increase the shear strength significantly.

4. Conclusions

An experimental program was conducted to investigate the influence of steel, glass and steel-glass hybrid fibres on the compressive strength, modulus of elasticity, indirect tensile strength and shear strength of RPC. Based on the experimental results of this study, the following conclusions can be drawn.

1. The ratio of the compressive strength at 7 days to the compressive strengths at 28 days for NF-RPC was 88%. The ratio of compressive strength at 56 days to the compressive strengths at 28 days for NF-RPC was 113%. The ratio of compressive strength at 7 days to the compressive strengths at 28 days for NF-RPC was found to be about 33% higher than that of normal strength concrete. The ratio of compressive strength at 56 days to the compressive strengths at 28 days for NF-RPC was found to be similar to that of normal strength concrete. The addition of 1.5% by volume of steel fibres in the RPC increased the average compressive strength by 6.6%, while the addition of 1.5% by volume of the glass and the hybrid (steel plus glass) fibres in the RPC decreased the average compressive strength by 10% and 5.5%, respectively, compared to the average compressive strength of NF-RPC.
2. The average modulus of elasticity of NF-RPC was 39 GPa. The SFR-RPC achieved average modulus of elasticity marginally higher than that of NF-RPC, and HFR-RPC achieved average modulus of elasticity equals to that of NF-RPC. In contrast, the average modulus of elasticity for GFR-RPC was 5% lower than the modulus of elasticity for NF-RPC.

3. Average splitting tensile strength of NF-RPC increased by about 30% and 20% with the addition of the steel and hybrid steel-glass fibres, respectively. However, the average splitting tensile strength of NF-RPC decreased by 25% after the addition of the glass fibres.
4. The average shear strength of RPC under direct shear demonstrated a significant improvement with the addition of the fibres (steel, glass and steel-glass fibres). The SFR-RPC achieved average shear strength about 150% higher than that of NF-RPC. Also, the average shear strengths of GFR-RPC and HFR-RPC were about 60% and 120%, respectively, higher than that of NF-RPC.

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Table 1 Properties of steel and glass fibres

Property	Steel fibre [22]	Glass fibre [23]
Length (mm)	13	13
Diameter (mm)	0.2	1.3
Aspect ratio (length/diameter)	65	10
Density (g/cm^3)	7.8	2.8
Tensile Strength (MPa)	2500	1500

Table 2 Experimental mechanical properties of NF-RPC and FR-RPC at 28 days *

Mix notation	Compressive strength (MPa)	Average flow diameter (mm)	Modulus of elasticity, E (GPa)	Indirect tensile strength, T (MPa)	Shear strength, τ (MPa)
NF-RPC	90	200	39	7.6	10
St. Dev.	1.52	-	2.12	0.23	1.41
SFR-RPC	96	190	40	9.9	25
St. Dev.	2.51	-	2.83	0.26	3.05
GFR-RPC	81	180	37	5.7	16
St. Dev.	2.64	-	2.52	0.32	2.30
HFR-RPC	85	185	39	9.1	22
St. Dev.	2.46	-	2.51	0.37	2.64

* Each result is an average of three tested specimens

Fig. 1 Steel and glass fibres

Fig. 2 Flow table test

Fig. 3 Test setup for axial load-axial deformation behaviour

Fig. 4 Test setup for splitting tensile strength

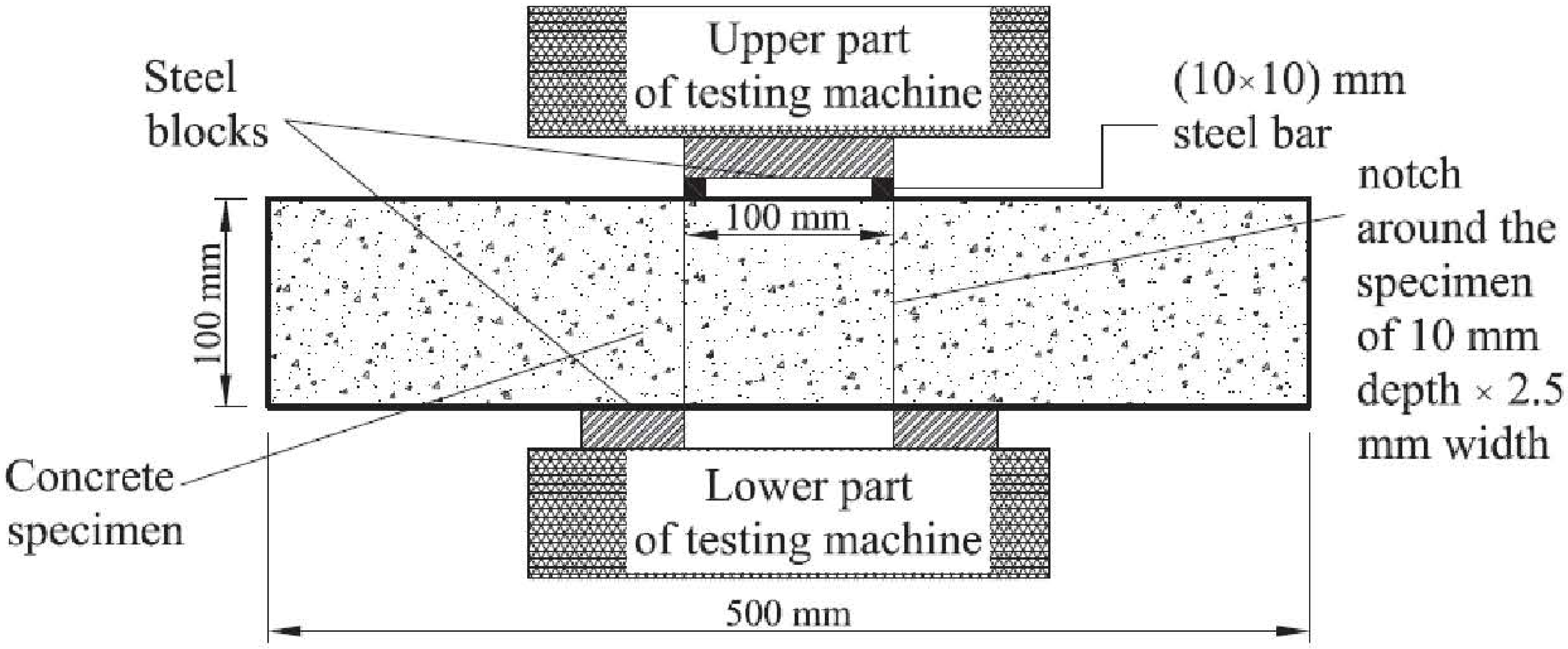

Fig. 5 Schematic of the direct shear test

Fig. 6 Test setup for shear strength

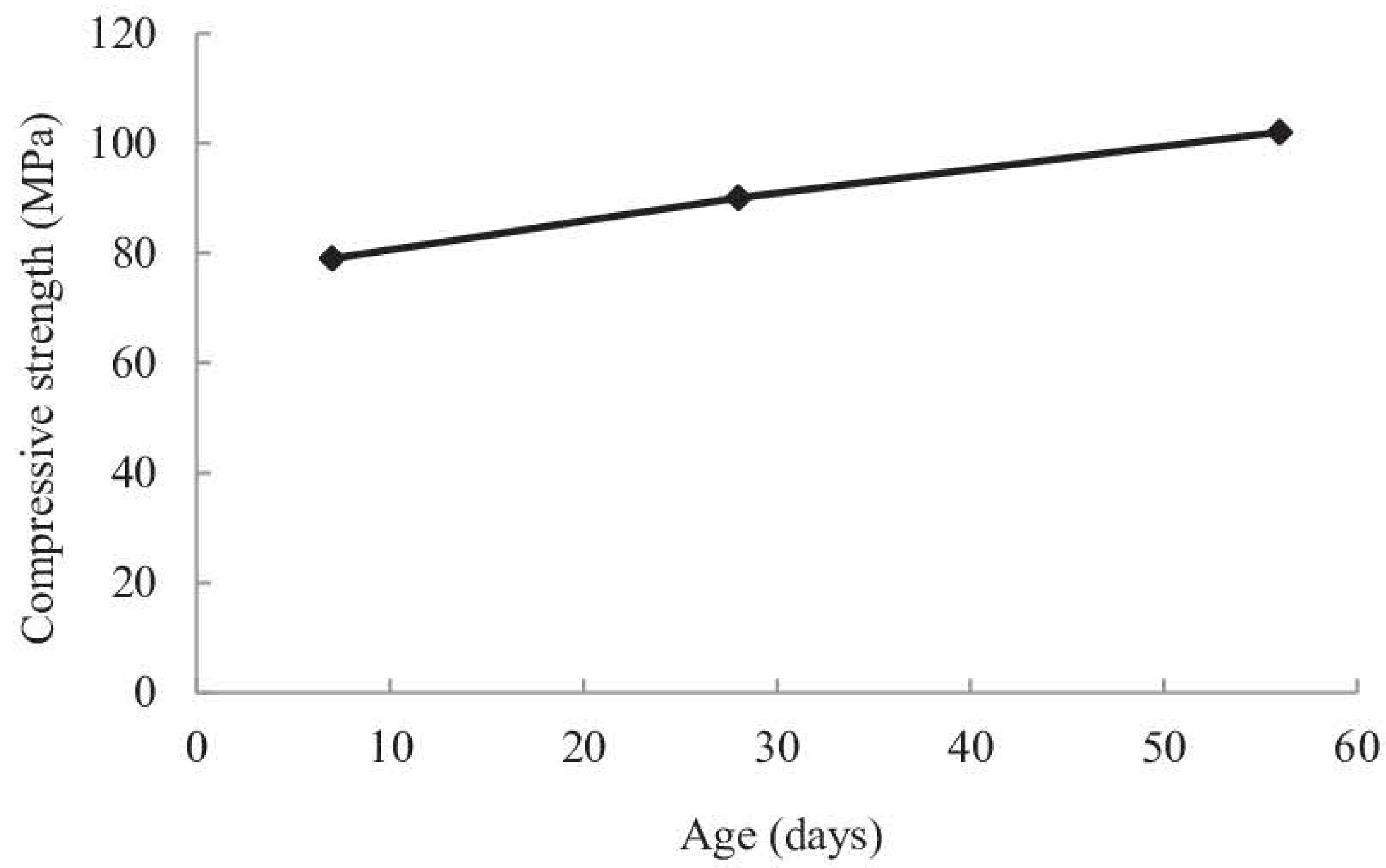

Fig. 7 Age versus compressive strength for NF-RPC

Fig. 8 Typical failure modes of NF-RPC and FR-RPC under compressive axial load

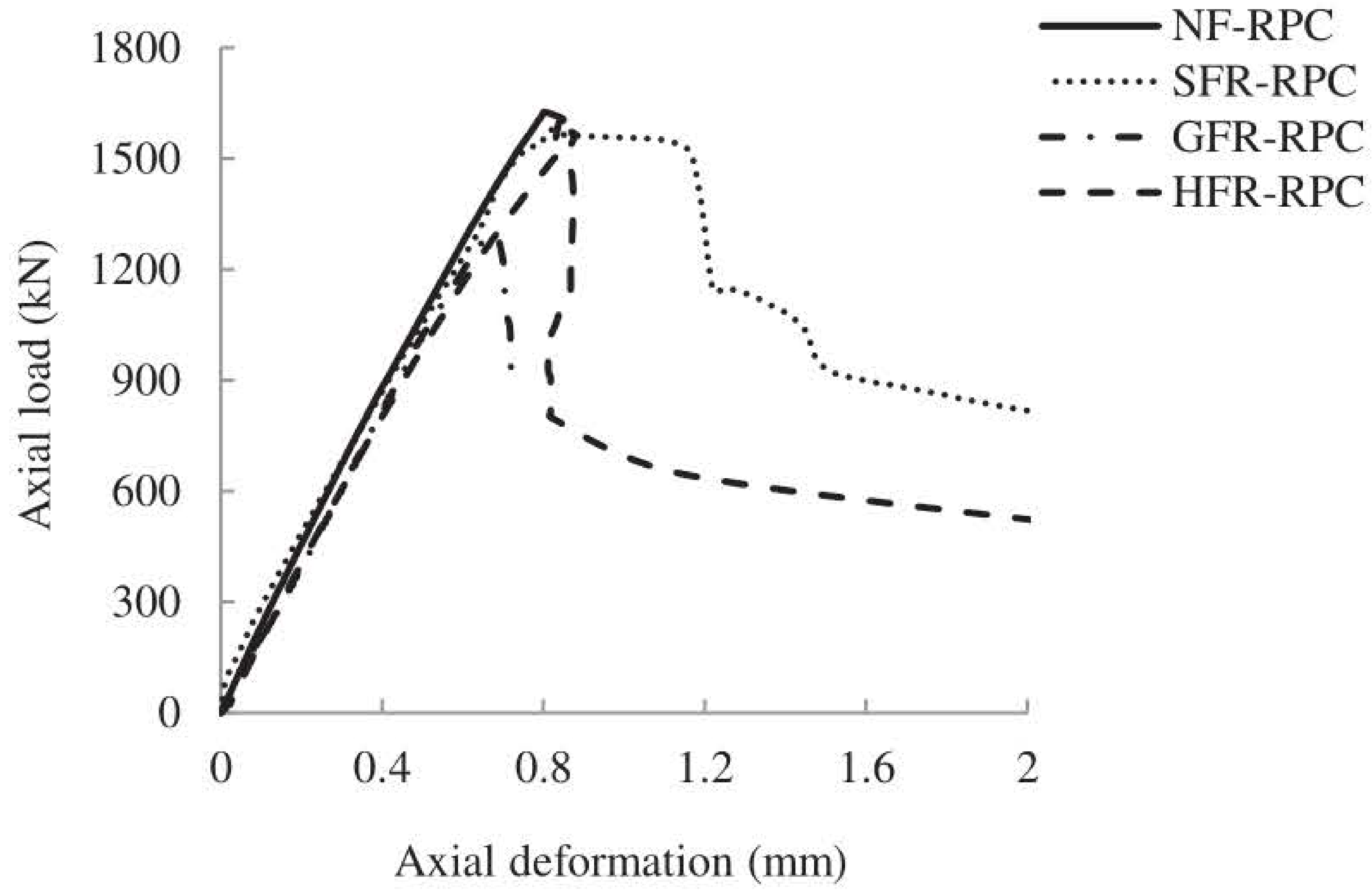

Fig. 9 Typical axial load-axial deformation behaviour of NF-RPC and FR-RPC

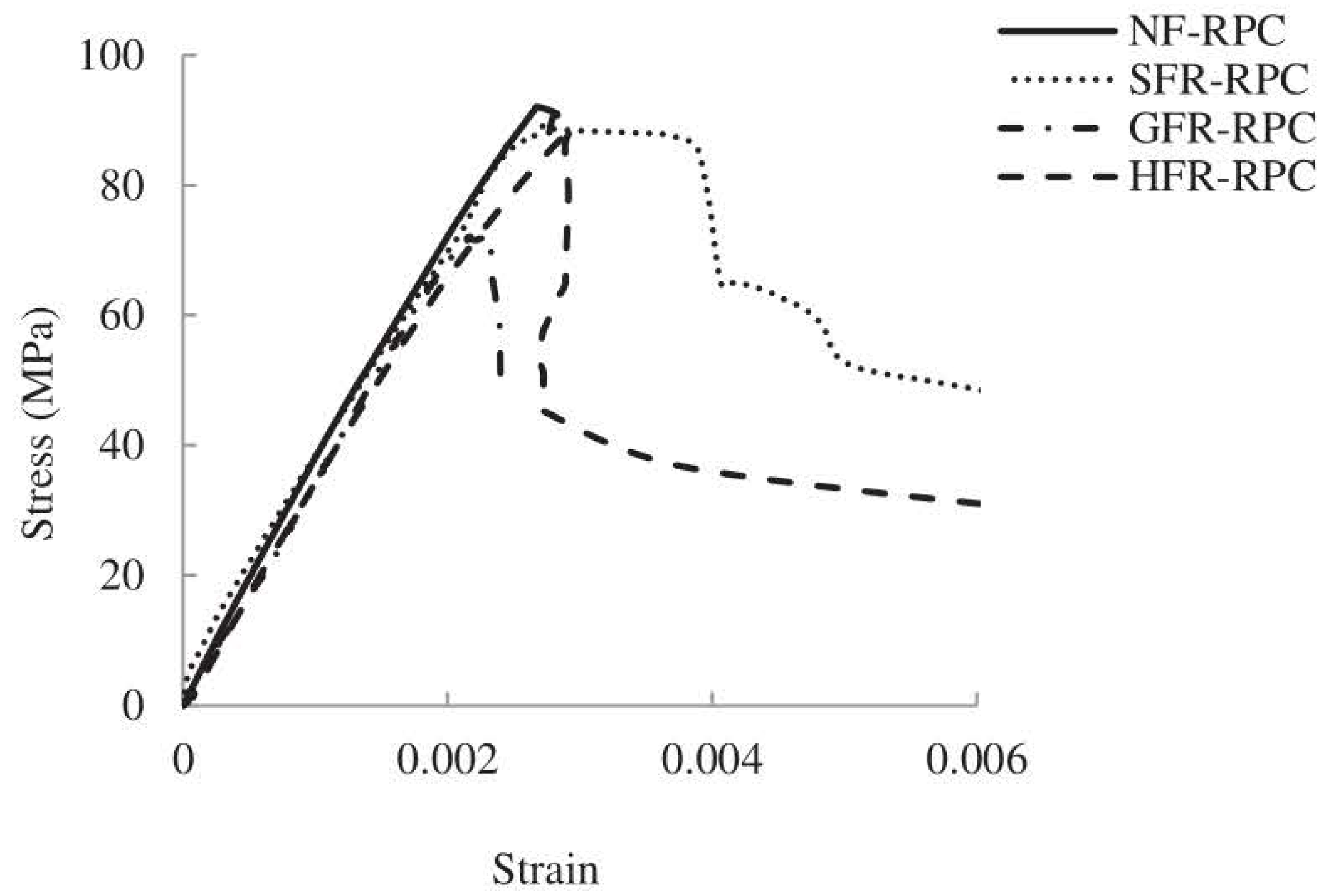

Fig. 10 Typical stress-strain behaviour of NF-RPC and FR-RPC

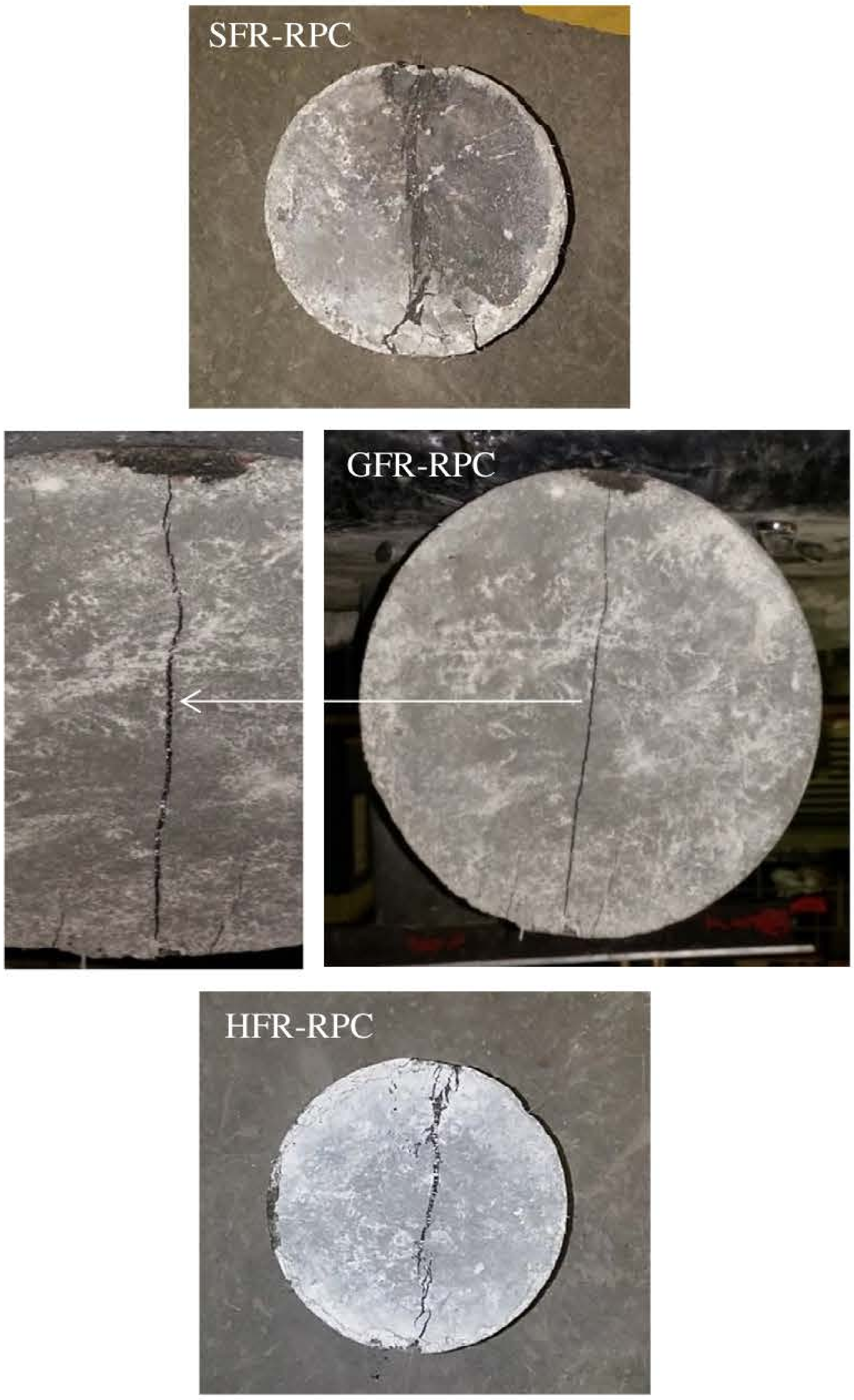

Fig. 11 Typical failure modes of SFR-RPC, GFR-RPC and HFR-RPC under splitting tensile test

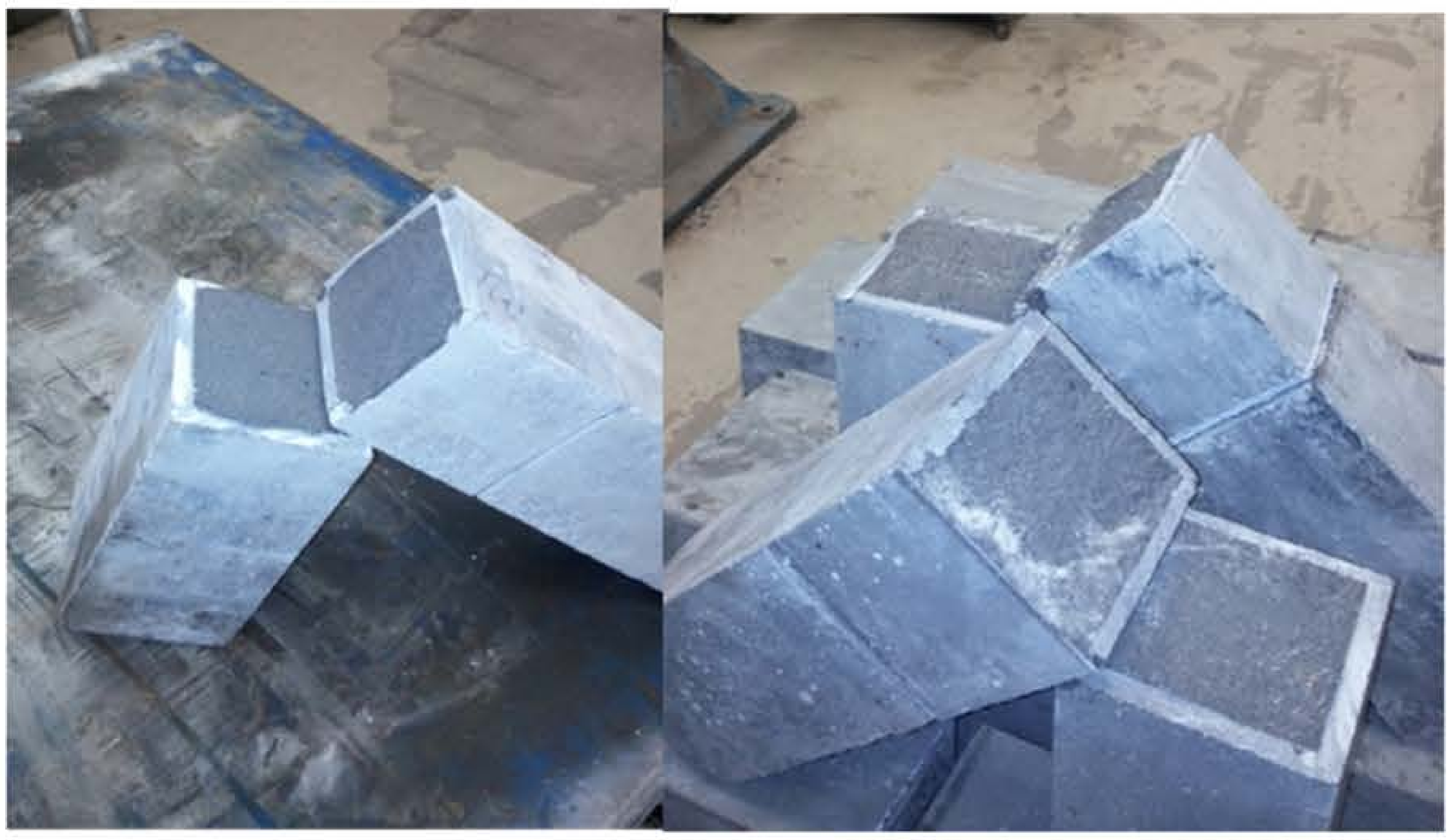

Fig. 12 Typical failure modes of NF-RPC and FR-RPC under direct shear